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Barbara Hayes-Roth
with the assistance of Stephanie Cammarata, Sarah E. Goldin,
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This report)

Summarizes a three-year research project investigating the cognitive processes underlying human planning behavior. The project focused on problems analogous to the naval tactical planning problem: How should the decisionmaker move force units from their current locations to particular task force objectives? Major project tasks included developing a cognitive model of the planning process, implementing the model as a computer simulation and evaluating its performance, and conducting empirical research to test the basic assumptions of the model and to identify important task and individual difference factors that affect the planning process. Based on the results of these research efforts, a preliminary set of guidelines are presented for improving the selection and training of planners and for designing effective planning aids.

PREFACE

This report summarizes the findings of a three-year investigation of cognitive processes in planning and control, conducted for the Office of Naval Research under Contract No. N00014-78-C-0039.

The project entailed developing a cognitive model of the planning process, formalizing the model as a computer simulation, and collecting a variety of empirical and computational data. The findings should interest practitioners and researchers concerned with planning performance and the development of planning aids. More detailed discussions of project subtasks can be found in the following Rand publications:

Cognitive Processes in Planning, by Barbara Hayes-Roth and Frederick Hayes-Roth, R-2366-ONR, December 1978.

Decisionmaking During the Planning Process, by Barbara Hayes-Roth and Perry W. Thorndyke, N-1213-ONR, October 1980.

Flexibility in Executive Strategies, by Barbara Hayes-Roth, N-1170-ONR, September 1980.

Individual Differences in Planning Processes, by Sarah E. Goldin and Barbara Hayes-Roth, N-1488-ONR, June 1980.

Modeling Planning as an Incremental, Opportunistic Process, by Barbara Hayes-Roth, Frederick Hayes-Roth, Stanley J. Rosenschein, and Stephanie Cammarata, N-1178-ONR, June 1979.

Estimation of Time Requirements During Planning: Interactions Between Motivation and Cognition, by Barbara Hayes-Roth, N-1581-ONR, November 1980.

SUMMARY

Planning and control are primary components of effective management. *Planning* refers to formulating an intended course of action aimed at achieving a goal; *control* refers to monitoring and guiding the plan to a successful conclusion. This report summarizes the results of a three-year research effort investigating the cognitive processes underlying planning and control.

The project focused on problems analogous to the naval tactical planning problem: How should the decisionmaker move force units (ships) from their current locations to particular task-force objectives? For pragmatic reasons, we did not use real tactical planning problems in the research. However, our research tasks preserved the basic features of the tactical planning problem: The planners had to consider the special characteristics of individual units, the locations of and routes for approaching target destinations, the goals to be achieved at target destinations, and other risks and constraints.

Our first subtask was to develop a cognitive model of the planning process. This model, which we call the *opportunistic planning model*, views planning as the cooperative efforts of many independent plan *specialists*, or condition-action rules. Each specialist makes tentative decisions for incorporation into the developing plan and posts them in a common data structure, the *blackboard*. Each specialist can examine prior decisions posted on the blackboard and consider them, along with its own "knowledge," in generating new decisions. The blackboard is partitioned into several *planes*, representing different conceptual categories of decisions. These include (a) metaplan decisions—what general approach to take to the problem; (b) plan decisions—what actions to take; (c) plan abstraction decisions—what kinds of actions are desirable; (d) world knowledge decisions—what information motivates particular plan decisions; and (e) executive decisions—how to organize the planning process itself. Each of these planes is further partitioned into several *levels of abstraction*. The blackboard structure restricts the amount of information each specialist must consider in order to generate a decision. It also provides a conceptual framework for understanding and analyzing the planning process. This process proceeds through a series of cycles during which individual specialists inspect information on the blackboard and post new decisions. The scheduling of individual specialists is controlled by executive decisions based on focus of attention and recency of invocation. The process ordinarily continues until the planner has integrated mutually consistent decisions into a satisfactory plan.

We implemented a computer simulation of the opportunistic model in the programming language INTERLISP. The simulation contains an internal representation of the blackboard structure and about forty specialists. Its performance is quite similar to that of a human planner. The simulation and the human planner produce plans with similar strengths and weaknesses. In addition, the "protocols" they produce while planning contain many of the same intermediate decisions, as well as many common general characteristics.

Empirical research performed in this study encompassed a variety of tasks:

1. Protocol analyses confirmed the basic assumptions of the opportunistic planning model: (a) that people make decisions representing each of the postulated levels of abstraction on all five planes of the planning blackboard; and (b) that people generate successive decisions opportunistically, rather than by working systematically through the planning space.

2. We obtained more rigorous support for these assumptions in experimental investigations of subjects' judgments about the similarity of individual planning decisions and investigations of the influence of early planning decisions on subsequent decisions.

3. Another set of experiments demonstrated subjects' abilities to adopt alternative general planning strategies. Subjects adopted particular strategies in response to explicit instruction and by transferring strategies adopted on previous, similar planning tasks.

4. A series of detailed protocol analyses revealed three categories of individual differences in planning behavior: Good planners made decisions in all categories specified on the planning blackboard, whereas poor planners operated in a more restricted region of the blackboard; good planners showed greater attentional flexibility than poor planners; and good planners had many more planning specialists than poor planners. Based on these analyses, we developed a protocol for effective planning.

5. Correlational analyses suggested that several scenario characteristics might influence planning performance. These included the number of goals under consideration, the time available for achieving goals, and the difficulty of achieving all goals in the available time.

6. A series of studies on time estimation during planning revealed that subjects habitually underestimate the time required for planned tasks. Two factors seem to contribute to this tendency. The cognitive factor is subjects' inclination to plan at high levels of abstraction, failing to enumerate all time-consuming elements of planned activities. The motivational factor is subjects' tendency to generate low time estimates in response to a desire to accomplish all or most of the goals under consideration.

7. We developed an automatic plan evaluator to provide feedback to subjects on their planning performance. By interacting with the evaluator on several trials, subjects learned about relevant environmental contingencies and the criteria used to evaluate their plans. We then measured the quality of subjects' plans in terms of their asymptotic performance following these trials.

Based on the results summarized above, we propose a set of principles for improving planning performance:

- The criteria for selecting planners should be a large-capacity working memory, attentional flexibility, and strategic flexibility.
- Planners should be taught the importance of abstract plans, world knowledge, and metacognition.
- Planners should also be taught domain-specific planning heuristics, the value of controlled opportunism, general planning strategies, and cognitive strategies for resource estimation.

- Three training methods should be used: explicit instruction, induction of illustrative experiences, and illustration of effective planning by means of a computer simulation.
- Three planning aids should be employed : a resource estimator, a plan evaluator, and a planning collaborator.

While these suggestions must be regarded as preliminary, they provide a detailed framework for future research.

ACKNOWLEDGMENTS

CONTENTS

I. INTRODUCTION

Planning and control constitute two primary components of effective management. *Planning* refers to formulating an intended course of action aimed at achieving some goal; *control* refers to monitoring and guiding the plan to a satisfactory conclusion.

Because planning and control processes are ubiquitous, a good model of these processes should apply to the performance of many tasks. The research project described in this report focused on problems similar to the naval tactical planning problem: How should the decisionmaker move force units (ships) from their current locations to particular task-force objectives? In approaching such a problem, the decisionmaker must consider the special characteristics of individual units (e.g., different drafts or detection ranges), the locations of and routes for approaching target destinations, the goals to be achieved at target destinations, and additional risks and constraints.

Currently, there are no formal methods for solving these problems. Because of their computational complexity, tactical planning problems are not amenable to either operations research procedures or computational algorithms. People apparently solve these problems by attending selectively to critical problem components and applying heuristic methods. The goal of the research reported here was to improve our understanding of the cognitive processes people bring to bear on tactical planning problems and to infer principles for the improvement of planning performance. This report summarizes our findings and presents a set of preliminary principles.

The remainder of the report is organized as follows: Section II describes the task used in our research. Section III characterizes the cognitive model developed to describe and explain human planning behavior and to guide the subsequent research. Section IV describes a computer simulation of the planning model and compares its performance to the performance of human planners. Section V summarizes a variety of empirical research on human planning performance. Section VI presents a set of preliminary principles for the improvement of planning performance.

II. THE RESEARCH TASK

For pragmatic reasons, we did not use real tactical planning problems in our research. The empirical studies required large numbers of readily available subjects, and it would have been very difficult and expensive to use only subjects with prior knowledge of and expertise in tactical planning. Therefore, the research used an analogue of the tactical planning problem—an errand-planning task.

For this task, we presented subjects with a scenario that specified a starting time and location, an ending time and fi.....i destination, a list of intermediate target destinations and associated goals, and certain additional constraints. Subjects then formulated plans for achieving a subset of the requested goals under the constraints specified in the scenario. A sample scenario follows:

> You have just finished working out at the health club. It is 11:00 and you can plan the rest of your day as you like. However, you must pick up your car from the Maple Street parking garage by 5:30 and then head home. You'd also like to see a movie today, if possible. Show times at both movie theaters are 1:00, 3:00, and 5:00. Both movies are on your "must see" list, but go to whichever one most conveniently fits into your plan. Your other errands are as follows:
>
> - Pick up medicine for your dog at the vet.
> - Buy a fan belt for your refrigerator at the appliance store.
> - Check out two of the three luxury apartments.
> - Meet a friend for lunch at one of the restaurants.
> - Buy a toy for your dog at the pet store.
> - Pick up your watch at the watch repair.
> - Special-order a book at the bookstore.
> - Buy fresh vegetables at the grocery.
> - Buy a gardening magazine at the newsstand.
> - Go to the florist to send flowers to a friend in the hospital.

Figure 1 shows the map subjects used in forming their plans.

Like the sample scenario, most of the scenarios we used did not provide enough time to accomplish all of the intermediate goals. Therefore, the subjects' task required them to (a) decide which goals to achieve, (b) decide the order in which to achieve individual goals, (c) plan routes between successive destinations, and (d) decide how much time to allocate for individual goals and for traveling between destinations.

The errand-planning task is very similar to the tactical planning task: How should the decisionmaker move units (people) from their current locations to particular task objectives? In approaching such a problem, the decisionmaker must consider the special characteristics of individual units (e.g., mode of transportation, ability to carry burdens), the locations of and routes for approaching target destinations, the goals to be achieved at target destinations, and additional risks and constraints.
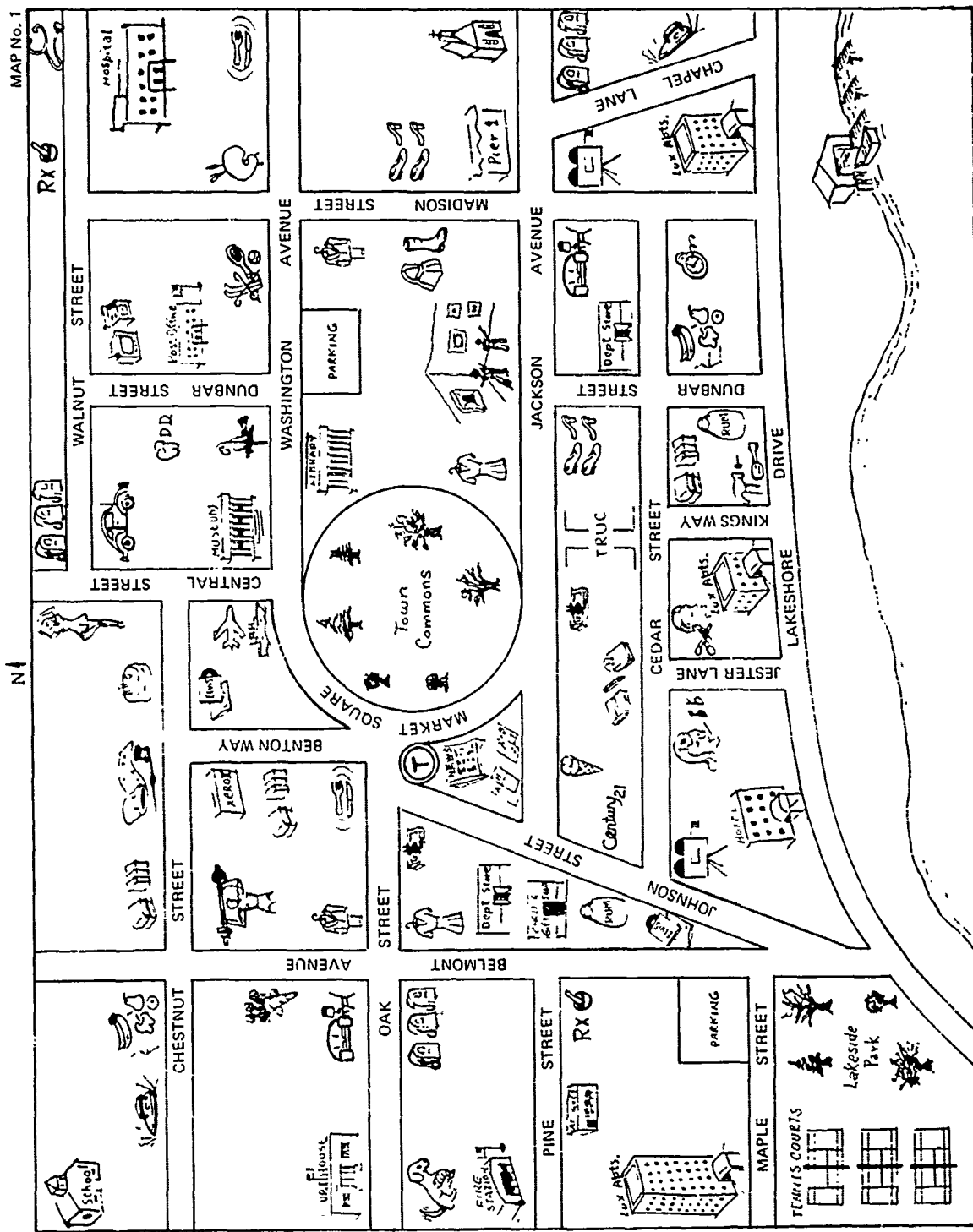
Fig. 1—Map subjects used in forming their plans

III. A COGNITIVE MODEL OF THE PLANNING PROCESS

The first project subtask was to develop a model of the cognitive processes people use during planning. This model, the *opportunistic planning model*, views planning as the cooperative effort of many independent plan *specialists*. Specialists may be thought of as mental rules or programs. Each specialist makes tentative decisions for incorporation into the developing plan. Different specialists have different types of planning knowledge and hence influence different aspects of the plan. For example, some specialists suggest high-level, abstract additions to the plan, while others suggest detailed sequences of specific actions.

In the opportunistic planning model, specialists record their decisions in a common data structure, the *blackboard*. Each specialist can examine prior decisions posted on the blackboard, transform or combine that information with its own "knowledge," and generate new decisions. The blackboard is partitioned into several *planes* corresponding to different conceptual categories of decisions. Each plane is further partitioned into several *levels of abstraction*. This blackboard structure restricts the amount of information each specialist must consider in order to generate a decision. It also provides a conceptual framework for understanding and analyzing planning processes. The remainder of this section discusses specialists, the blackboard structure, and control of the planning processes in more detail. Finally, it contrasts the proposed model with previous conceptions of the planning process.

SPECIALISTS

Specialists embody knowledge about different kinds of planning decisions and the situations in which each kind is appropriate. The model operationalizes specialists as condition-action rules. For example, one specialist might state

> IF there is a requested errand near the current location,
> THEN record a decision to perform that errand next.

The condition component describes the circumstances under which the specialist can make a decision. The condition usually requires specific types of information to have been posted on the blackboard by other specialists, as well as the satisfaction of other, arbitrarily complex criteria. When the condition of a specialist has been satisfied, we say that the specialist has been *invoked*. The action component specifies the specialist's decisionmaking behavior. The action might post a new decision on the blackboard or modify a previously posted decision. Thus, specialists represent a set of heuristics for generating or modifying plan decisions based on recognized patterns of previous decisions.

BLACKBOARD STRUCTURE

As mentioned above, the blackboard contains five conceptual planes: *plan, plan*

abstraction, *world knowledge*, *executive*, and *metaplan*. Each of these partitions records a different kind of planning knowledge. The blackboard structure is shown in Fig. 2.

Plan, plan abstraction, and world knowledge decisions determine features of the developing plan. Decisions on the plan plane represent actions that the planner intends to take in the world. For example, in the errand-planning task, the planner might decide to go to the florist next or to travel down Jackson Avenue to get to the bank. Decisions on the plan abstraction plane characterize desired attributes of potential plan decisions, indicating the kinds of actions that the planner would like to take, without specifying the actions themselves. For example, the planner might decide to go to the closest errand next (without specifying the identity of that errand) or to organize the plan around spatial clusters of errands (without specifying the contents of those clusters). Decisions on the world knowledge plane record observations and computations regarding relationships in the task environment that might bear on the final plan. For example, a world knowledge decision might encode the fact that the florist is close to the current location, or that the bank, the shoe store, and the movie theater are clustered in the same neighborhood.

In contrast to these three planes, executive decisions determine the allocation of cognitive resources during the planning process: what kinds of decisions to generate first, what aspect of the plan to develop next, what specialist to bring to bear at a given point in the planning process. For example, the planner might decide to determine the best order for the errands before finding a route among them.

The metaplan plane contains more general decisions about how to approach the planning problem. Metaplan decisions reflect the planner's understanding of the
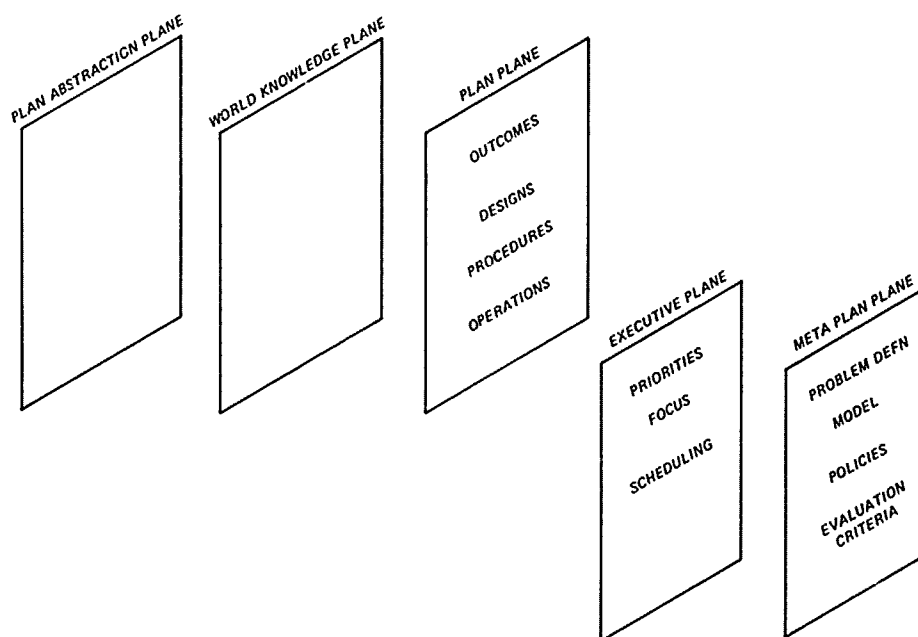

Fig. 2—Blackboard structure in the opportunistic planning model

problem, the methods he or she intends to apply to it, and the criteria he or she will use to generate and evaluate prospective plans. For example, the planner might decide to maximize plan efficiency at the expense of certain types of subgoals.

As mentioned above, the model further partitions each plane into several levels of abstraction. The plan abstraction, world knowledge, and plan planes each have four levels of abstraction that form a potential hierarchy, with decisions at each level specifying a more refined plan than those at the next higher level. Decisions at the highest level determine a plan's *outcomes:* which errands will be accomplished when the plan is executed. For example, outcome decisions on the plan abstraction, world knowledge, and plan planes might be

a. I'll do all the most important errands.
b. The drugstore and the grocery are the most important errands.
c. I'll definitely go to the drugstore and the grocery.

Decisions at the next lower level determine the plan's *design*, the overall spatial-temporal organization of planned activities. For example, decisions on the three planes at this level might be

a. I'll organize the plan around spatial clusters of errands.
b. There is a cluster of errands in the southwest corner.
c. I'll head toward the southwest cluster, doing errands on the way.

Decisions at the next lower level determine the plan's *procedures*, that is, the ordering of individual errands. For example, three such decisions might be

a. I'll do the closest errand next.
b. The florist is closest.
c. I'll go to the florist next.

Finally, decisions at the lowest level of abstraction determine the plan's *operations*, the details of performing specific errands or traveling from one to another. For example, three such decisions might be

a. I'll take the shortest route to the next errand.
b. Belmont Street is the shortest route between the parking lot and the florist.
c. I'll travel via Belmont Street to get to the florist.

The executive plane has three levels of abstraction. At the highest level, *priority* decisions establish principles for allocating cognitive resources during the entire planning process (e.g., I'll decide which errands to do before deciding when to do any of them). At the next lower level, *focus* decisions indicate what kind of decisions to make at a particular point in the planning process (e.g., Now I'll figure out the best route from the grocery to the drugstore). Finally, *scheduling* decisions resolve any remaining conflicts between competing invoked specialists, choosing a particular specialist to execute its action next.

The four levels of the metaplan plane, *problem definition, problem-solving model, policies,* and *evaluation criteria,* do not produce a neat hierarchy. However, they emphasize different aspects of the subject's approach to the planning problem: his or her representation of the task and its goals, resources and constraints (problem definition), the general strategy the planner assumes in generating a solution

(problem-solving model), a set of global constraints and desirable features for the developing plan (policies), and a set of dimensions against which the planner can evaluate tentative plans (evaluation criteria).

CONTROL OF THE PLANNING PROCESS

The planning process proceeds through a series of cycles during which specialists read information from the blackboard and take subsequent action. On any cycle, a number of specialists may be invoked—that is, their conditions may have been satisfied by the appearance of some prior decision on the blackboard. An executive decision determines which of the invoked specialists executes its action, generating a new decision and recording it on the blackboard. This new decision will invoke additional specialists, beginning a new cycle. The process will ordinarily continue until the planner has integrated mutually consistent decisions into a satisfactory plan.

The executive decisions that schedule invoked specialists play a central role in the performance of the simulation. These decisions reflect previous decisions about areas of the blackboard for focusing attention. Other things being equal, specialists that operate in these areas will be given priority. The executive also considers recency of invocation. Other things being equal, recently invoked specialists will be given priority. These two considerations, focus of attention and recency of invocation, enable the executive to schedule invoked specialists so as to produce a variety of intelligent decision sequences.

CONTRASTS BETWEEN THE OPPORTUNISTIC PLANNING MODEL AND PREVIOUS PLANNING MODELS

The proposed model contrasts with previous models of planning as a systematic, "top-down" process. These earlier models assume that a planner begins by making very abstract plans which guide and restrict subsequent development of more detailed plans. While the opportunistic model recognizes the important role of top-down planning, it also incorporates "bottom-up" planning processes. That is, the planner sometimes makes very detailed plans which inspire new or revised plans at higher levels of abstraction.

A second difference concerns the relative completeness attributed to abstract plans. The earlier models assume that initial abstract plans must be complete and fully integrated at some point in the planning process. By contrast, the opportunistic model assumes that planning is incremental and will rarely produce complete plans at all levels of abstraction. It assumes that planners make tentative decisions, without requiring that each one fit into a current, well-integrated plan. Alternative plans and subplans can develop simultaneously, being integrated into a final complete plan at the planner's discretion.

A third difference concerns the presumed structure of the planning process. Earlier conceptions treated plans as hierarchical structures, while the opportunistic model treats plans as more general, heterarchical structures. While they are well-structured, the many categories of decisions embodied in the proposed planning blackboard do not fit into any obvious hierarchical structure.

The following sections present a variety of evidence supporting the opportunistic model. They do not present a detailed analysis of the contrasting predictions of the opportunistic model and the top-down, hierarchical model. However, such analyses can be found in the technical reports noted in the Preface (p. iii).

In addition to the empirical evidence, we might speculate on the relative merits of hierarchical versus opportunistic planning. On one hand, the orderly, systematic nature of the top-down process and the simplicity of its hierarchical structure argue in its favor. One might also argue that a top-down process would minimize memory load—the planner could restrict attention to a single area of the hierarchy, rather than attending intermittently to several different areas of the planning space.

On the other hand, planning in tasks fraught with complexity and uncertainty might benefit from less of the discipline imposed by a strictly top-down process. For such tasks, general problem-solving methods may not exist or may be computationally intractable. More importantly, a multidirectional process might produce better plans. Rather than restricting consideration to the obvious refinements of a fixed set of abstract plans, the planner can develop novel high-level plans suggested by low-level observations and decisions. Thus, the bottom-up component in multidirectional processing provides a potentially important source of innovation in planning.

IV. COMPUTER SIMULATION OF THE OPPORTUNISTIC PLANNING MODEL

We have implemented a computer simulation of the planning model in INTER-LISP. The simulation contains an internal representation of the map shown in Fig. 1, a blackboard structure to organize planning decisions, and about forty specialists. We designed the specialists to model knowledge inferred from thinking-aloud protocols produced by human subjects during planning. These specialists are abstractions, rather than literal codings of the observed knowledge. For example, the statement, "I'll go to the drugstore next because it's close," is abstracted as

IF an errand has been planned,
THEN plan to perform the closest errand to the planned errand
next.

Thus, the simulation is not finely tuned to model any particular protocol or subject. It is capable of producing a great variety of decision sequences and a great variety of final plans.

We can evaluate two aspects of the simulation's performance: the plans it produces and the process by which it produces them. We discuss each of these below.

Figure 3 shows the plan one subject produced for the problem discussed above. Figure 4 shows one of the plans produced by the simulation. The two plans are quite similar. Both plans include all primary errands and at least some of the secondary errands. While the human subject included all secondary errands, the simulation included only one very convenient secondary errand. Although the simulation and the subject planned different routes, both routes are fairly efficient, though clearly suboptimal. Both the simulation and the subject planned to arrive at time-constrained destinations (e.g., the restaurant and the movie) at reasonable times. The major difference between the two plans lies in their relative "realism." The human subject's plan is quite unrealistic—one could not execute the complete plan in the time available for doing so. The simulation's plan is somewhat more realistic, primarily because it omits many of the secondary errands.

As mentioned earlier, the simulation is capable of producing a variety of plans. Other "runs" of the simulation produced plans that differed more markedly from this subject's plan. If we experimented further with the simulation, it would probably produce plans that more closely resembled the subject's plan. The present exercise simply demonstrates the simulation's ability to produce plans that are quite similar to those produced by human planners. This is an important sufficiency test of the opportunistic model.

Like the human subject, the simulation produced a planning protocol—the series of decisions underlying the final plan. Figure 5 shows an excerpt from the subject's protocol, and Fig. 6 shows a corresponding excerpt from the simulation's protocol—decisions 10–22. (The protocol actually produced by the simulation is a series of decision "nodes" in list notation. Figure 6 presents the protocol in standard English for clarity.)

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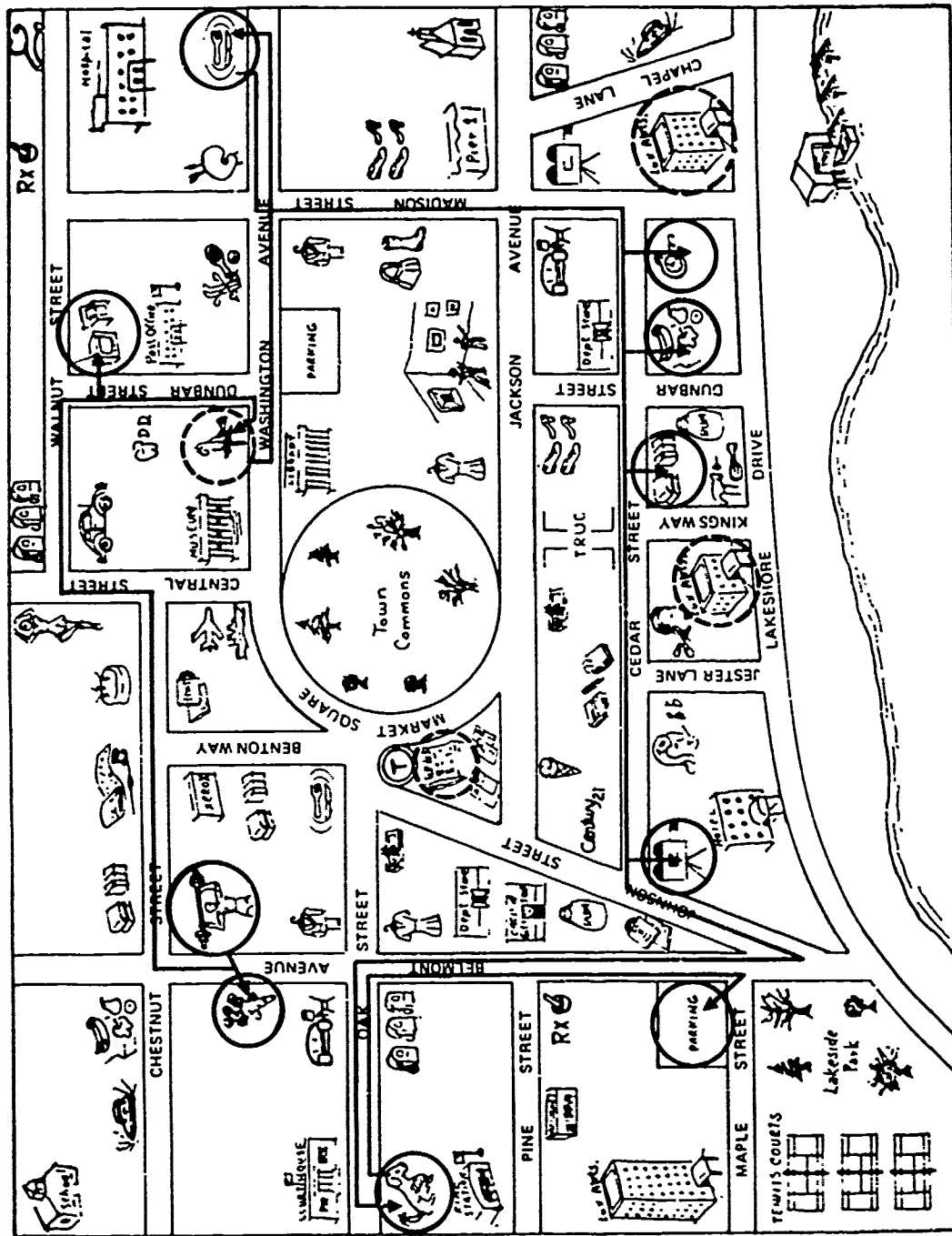
Fig. 3—Plan produced by the human subject
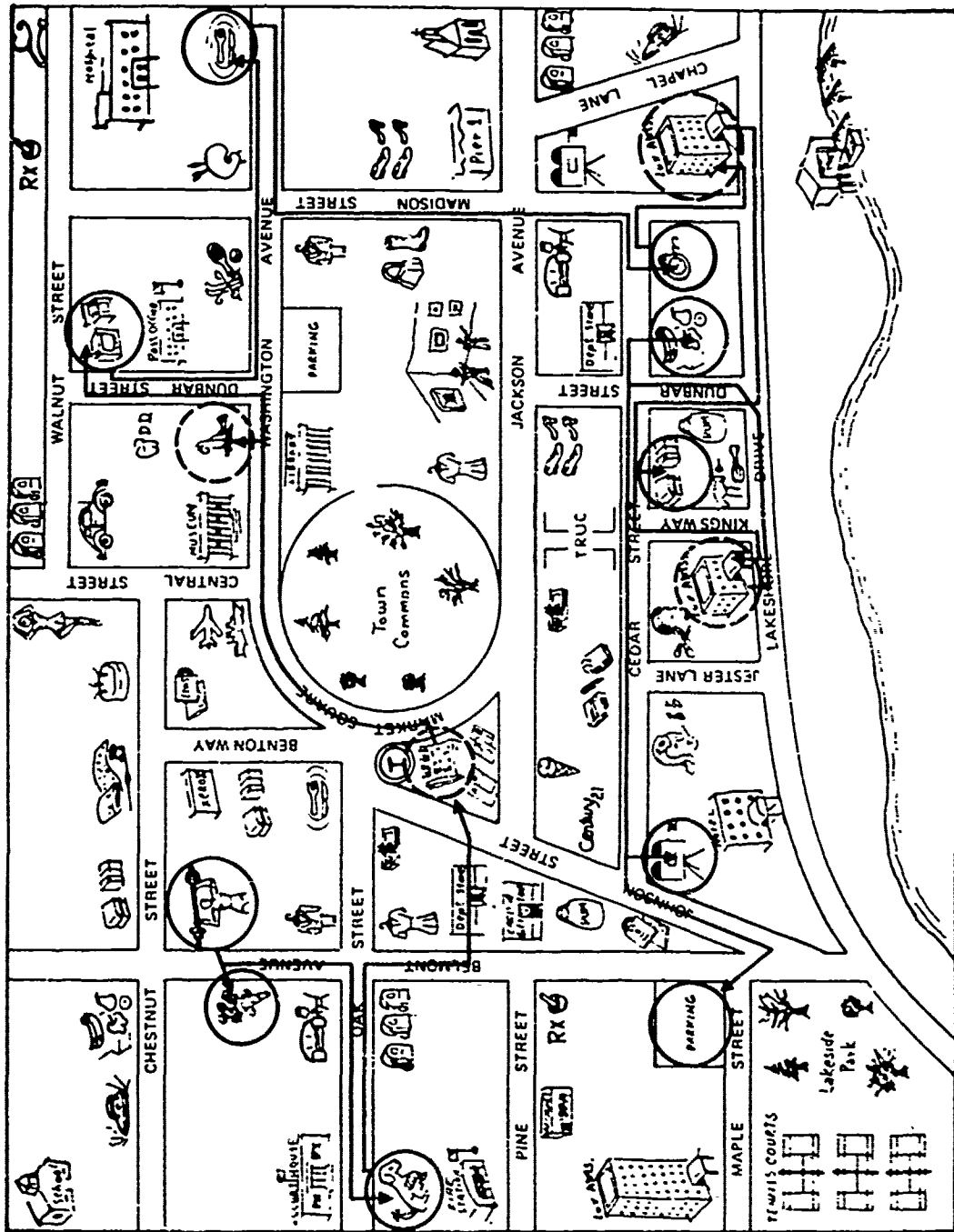
Fig. 4—Plan produced by the computer simulation

1-4 *Omitted*

* 5 All right. We are now at the health club.

* 6 What is going to be the closest one?

* 7 The appliance store is a few blocks away.

* 8 The medicine for the dog at the vet's office isn't too far away.

* 9 Movie theaters—let's hold off on that for a little while.

*10 Pick up the watch. That's all the way across town.

*11 Special-order a book at the bookstore.

*12 Probably it would be best if we headed in a southeasterly direction. Start heading this way.

*13 I can see later on there are a million things I want to do in that part of town.

Fig. 5—Excerpt from the human subject's protocol

1-9 *Omitted*

10 Work forward from the starting location.

*11 The starting location is the health club which is on Belmont Avenue.

12 Begin at the health club.

*13 Go to the closest errand next.

*14 The vet is on Oak Street.

*15 The appliance store is on Walnut Street.

16 The restaurant is on Washington Avenue.

*17 The watch repair is on Cedar Street.

*18 The bookstore is on Cedar Street.

19 The grocery is on Cedar Street.

*20 The watch repair, the bookstore, and the grocery are all in a cluster in the southeast part of town.

21 Organize the plan around spatial clusters.

*22 Proceed from the Health Club toward the southeast cluster.

Fig. 6.—Excerpt from the simulation's protocol

Decisions 10-22 of the simulation's protocol correspond quite closely to items 5-8 of the subject's protocol. In these items, the subject identified the health club as the starting location, decided to schedule the closest errand to the health club next, located several errands on the map in his search for the closest errand, detected a cluster of errands in the southeast part of town, and, accordingly, decided to head in that general direction.

Now consider the simulation's protocol. Decision 10 establishes a strategy of working forward from the starting location. Decisions 11 and 12 identify the starting location as the health club and establish it as the first errand in the procedure. Decision 13 establishes a strategy of going to the closest errand next. Decisions 14-19 locate individual errands on the map in a search for the closest errand to the health club. Decision 20 detects the cluster of errands in the southeast part of town. Decision 21 suggests organizing an overall design for the plan around the spatial cluster, and decision 22 does so

In addition to performing essentially the same functions as the subject, the simulation made many of the decisions explicitly declared in the subject's protocol. Common decisions are preceded by an asterisk in Figs. 5 and 6. The remainder of the simulation's protocol does not always mirror the subject's protocol as closely as does the section in Fig. 6. Because the simulation can produce a variety of decision sequences, other "runs" would produce protocols more or less similar to the subject's protocol. However, two factors limit the maximal similarity we might observe.

First, the simulation does not contain exactly the same set of specialists used by the subject. Thus, the simulation occasionally uses a specialist that is slightly different from the one the subject uses. This produces differences in both the protocols and the resulting plans. For example, in item 18 of his protocol, the subject decided to go from the health club to the vet on the way to the southeast part of town. At the same point in its protocol, the simulation decided to go from the health club to the appliance store on the way to the southeast part of town. Both were trying to find the closest errand along the way, but they used slightly different specialists, and as a consequence, they chose different errands.

Second, the simulation's executive is incomplete. On some cycles, two or more invoked specialists are equally attractive and the simulation chooses randomly among them. Frequently, this random choice fails to select the specialist the subject used at that point. In such cases, the protocols again diverge.

In our opinion, it would be unproductive to model the subject's performance at a level of detail sufficient to counteract the effects of these two factors. Therefore, we look for the same general features in the two protocols, rather than exact replication. Such commonalities are readily apparent. Both the simulation and the subject made decisions at various levels of abstraction on each of the five planes of the planning blackboard. Both exhibited many coherent decision sequences in which each decision appeared to build on its predecessors. However, both also frequently "jumped about" the planning blackboard, rather than working systematically along any particular dimension. In particular, the simulation and the subject both occasionally redirected or dramatically changed their own activity in response to fortuitous observations or computations on the available data (i.e., the map). Subsequent runs of the simulation produced protocols that differed considerably in the details of individual decisions but exhibited these same general features. Again, the simulation's planning behavior establishes the sufficiency of the opportunistic model to represent human planning behavior.

V. EMPIRICAL RESEARCH

We conducted a variety of empirical research tasks to test the assumptions of the opportunistic planning model, explore individual differences in planning performance, and characterize general properties of human planning performance. These studies and their results are summarized briefly below.

PROTOCOL ANALYSES

Our first empirical studies were informal analyses of protocols generated by subjects during planning. This exercise confirmed the basic assumptions of the opportunistic model: (a) that people make decisions representing each of the postulated levels of abstraction on all five planes of the planning blackboard, and (b) that people generate successive decisions opportunistically, rather than by working systematically through the planning space.

TESTING BASIC ASSUMPTIONS

An early set of experiments tested the two basic assumptions of the model in a more conventional experimental paradigm.

The levels-of-abstraction assumption predicts that human subjects will recognize the functional differences between decisions representing different levels of abstraction. Accordingly, in one experiment, we drew statements representing different levels from a pool of thinking-aloud protocols and asked a new set of theoretically naive subjects to sort them according to similarity. We then analyzed their sortings of the statements, using a hierarchical clustering program. The analysis produced groups of statements that corresponded exactly to the levels of abstraction postulated by the model. Thus, the postulated levels represent a set of cognitive categories for planning decisions.

The opportunism assumption predicts that a planner's prior decisions should influence the generation of subsequent decisions in both top-down and bottom-up directions. We tested two aspects of this prediction.

One experiment assessed the impact of a prior decision on the content of a subsequent decision. We gave subjects planning problems that required them to accept a particular initial decision (e.g., to go to the drugstore first). Subjects then chose a subsequent decision from two alternatives (e.g., to travel in a circle around town or to travel from west to east across town). By carefully controlling the prior decision, we were able to influence subjects to choose one particular option from the alternative subsequent decisions. This was true regardless of the levels of abstraction represented by prior and subsequent decisions.

Another experiment assessed the impact of a prior decision on the level of abstraction of a subsequent decision. Again we gave subjects planning problems that required them to make a particular initial decision and to choose a subsequent decision from two alternatives. In this case, one alternative represented a higher

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level of abstraction than the prior decision, while the other represented a lower level of abstraction. By carefully controlling the prior decision, we were able to influence the level of abstraction of the chosen subsequent decision.

These results supported the two basic assumptions of the opportunistic planning model.

GENERAL PLANNING STRATEGIES

A corollary of the opportunism assumption is that planners should be able to adopt alternative general planning strategies. In particular, they should be able to work top-down, developing the most general features of a plan before working out the details, or bottom-up, starting immediately with the details. The strategy subjects adopt has important consequences for both the ease of generating a plan and the quality of the plan produced. The top-down strategy is appropriate when time is limited. It provides the most efficient approach to developing a plan that satisfies severe time limitations. The bottom-up strategy is more appropriate when there are minimal time limitations. Five experiments investigated subjects' abilities and inclinations to adopt these alternative strategies.

Experiment 1 simply assessed subjects' predispositions to adopt each strategy. The results were straightforward: Most subjects adopted the bottom-up strategy regardless of which strategy was appropriate. As a consequence, for problems that imposed minimal time limitations, subjects produced good plans in a short period of time. However, for problems that imposed time limitations, subjects produced inferior plans and required longer to produce them. These results indicate that subjects have strong predilections toward adopting the bottom-up strategy rather than the top-down strategy.

Experiment 2 demonstrated that subjects can adopt either strategy when explicitly instructed to do so. It further documented the effect of the adopted strategy upon performance. When instructed to adopt the top-down strategy, subjects performed better on time-limited problems than on unlimited problems. When instructed to adopt the bottom-up strategy, the reverse was true.

Experiment 3 illuminated one of the ways in which planners acquire strategies, the transfer of previously successful strategies to similar problems. We instructed subjects to adopt one strategy or the other for several training problems. When given a new problem but no explicit instructions, subjects continued to use the strategy they used on the training problems. They transferred the old strategy regardless of its appropriateness, with the expected consequences for performance.

Experiment 4 demonstrated that many subjects can adopt both strategies appropriately if they are explicitly instructed to do so. However, a fair number of subjects continued to show a predilection toward adopting the bottom-up strategy.

Experiment 5 showed that a small number of subjects can acquire the ability to adopt both strategies appropriately on the basis of experience alone. We instructed subjects to adopt each strategy on each of two training problems. When given a new problem but no explicit instructions, a small number of subjects reliably transferred the appropriate strategy. However, many subjects did not do so and instead reverted to their original dependence upon the bottom-up strategy.

These results confirm the opportunistic model's prediction that subjects can use alternative general planning strategies and demonstrate the important conse-

quences these strategies have for planning performance. However, the results also show a predilection among most subjects to adopt a particular strategy and a reluctance among some subjects to alter this predilection.

INDIVIDUAL DIFFERENCES IN PLANNING

The opportunistic planning model embodies three potential dimensions for individual differences in planning behavior. First, individuals may differ in their operational planning spaces. Better planners may generate more decisions on certain planes of the blackboard or at particular levels of abstraction. Second, individuals may differ in their control processes. Better planners may show greater flexibility in their allocation of attention among different aspects of the planning problem. Third, individuals may differ in planning knowledge. Better planners may have more planning heuristics or more powerful planning heuristics.

We investigated these hypotheses by examining in detail a number of thinking-aloud protocols. We examined thirty protocols in all, six from each of five subjects. We evaluated each protocol with a composite score based on number of planned errands, importance of planned errands, satisfaction of temporal constraints specified in the problem, route efficiency, and temporal realism. Averaging scores for the six protocols from each subject, we generated a "planning score" for each subject. Subjects with high scores were identified as good planners; those with low scores were identified as poor planners. We then examined the relationship between each of the dimensions described above, as manifested in the protocols, and the subjects' planning scores.

We found that good planners make more metaplan and executive decisions than poor planners, suggesting that they exercise more conscious control over the planning process. Good planners also make more world knowledge decisions, suggesting that they are more sensitive to available information about the plan execution environment. We also found that good planners make more decisions at high levels of abstraction. This is consistent with our findings on general planning strategies, suggesting that good planners recognize the importance of a global approach to some planning problems, while poor planners rely more heavily on purely bottom-up planning strategies.

We found that good planners exhibit greater attentional flexibility than poor planners. They more frequently shift their focus of attention among the different planes of the planning blackboard and among different temporal loci within the plan itself.

Finally, we found that good planners have more planning heuristics as well as more powerful planning heuristics than poor planners. This was true for heuristics applying on each of the five planes of the planning blackboard.

Based on these results, we developed a preliminary protocol for effective planning in this domain:

1. Identify the most important errands.
2. Identify spatial clusters of errands
3. Assess constraints on the plan.
4. Establish evaluation criteria.

5. Choose a subset of the errands as plan objectives, based on importance, location, time limitations, constraints, etc.
6. Anchor the plan with temporally constrained objectives.
7. Establish a general design for the plan.
8. Plan forward and backward from anchored objectives in accordance with the design.
9. Evaluate the plan against established criteria throughout the process.

EFFECTS OF SCENARIO CHARACTERISTICS

Scenario characteristics can have important effects on the planning process and the plan produced. The opportunistic planning model suggests that certain characteristics should interact with particular planning heuristics (e.g., the interaction of time limitations with general planning strategy). However, there may be other scenario characteristics that have more general effects on planning performance. Accordingly, we conducted a correlational study relating a variety of scenario characteristics to several measures of planning performance. The results suggested the following relationships:

1. Planning time increases with the number of goals considered and with the time available for achieving goals. This relationship reflects the increasing complexity of the planning task as number of goals and execution time increase.
2. Subjects are uniformly unrealistic. They consistently overestimate what they can accomplish in the time available to execute their plans. Further, as the difficulty of achieving all of the goals in the available time increases, subjects become increasingly unrealistic.
3. As the difficulty of achieving all of the goals in the available time increases, subjects plan to achieve fewer goals and less important goals. Thus, they sacrifice both quantity and quality as the task becomes more difficult.

REALISM IN PLANNING

One of the most provocative findings revealed by the correlational study summarized above was subjects' tendency to overestimate what they could accomplish in the time available for plan execution. We conducted several additional experiments to investigate this phenomenon further.

The first experiment replicated the original results in an experimental paradigm. This experiment confirmed subjects' tendency to overestimate what they can accomplish and showed that the tendency increases as the number of goals considered increases or as the time available for achieving goals decreases. It also suggested that subjects are not entirely insensitive to time limitations. As time stress increased in either of these two ways, subjects responded appropriately by planning a smaller proportion of the goals under consideration. However, they failed to reduce their aspirations sufficiently to satisfy specified time limitations.

We generated two hypotheses to explain subjects' unrealistic planning behavior. The cognitive hypothesis assumes that people tend to estimate time require-

ments at high levels of abstraction. In so doing, they fail to enumerate all of the time-consuming details of planned actions, and as a consequence, they consistently underestimate the time required to perform them. The motivational hypothesis assumes that people are biased by their aspirations. They wish to achieve all of the goals under consideration and this influences their estimates of required times. The two hypotheses are not mutually exclusive; both may contribute to the phenomenon.

To test the cognitive hypothesis, we required subjects to estimate time requirements at three different levels of abstraction. At the most general level, they gave quick estimates of the time required to achieve a set of goals. At an intermediate level, they estimated the times required to achieve each goal in a set of goals. At the more specific level, they estimated the time required to perform the component actions entailed in each goal in a set of goals. The results confirmed the hypothesis; subjects produced longer time estimates at lower levels of abstraction than at higher levels.

To test the motivational hypothesis, we gave subjects two types of planning problems, differing only in the importance of the goals under consideration. We reasoned that problems specifying very important goals should produce high motivational states, while those specifying moderately important goals should produce lower motivational states. Under the motivational hypothesis, subjects should plan more unrealistically as the importance of the goal is increased. The results confirmed this prediction. Subjects' plans were more unrealistic for problems specifying very important goals than for problems specifying moderately important goals.

These results suggest that subjects' tendency to plan more than they can accomplish in the available time reflects both cognitive and motivational factors.

PLAN EVALUATOR

It is often difficult to assess planning performance because of the inherent ambiguity in defining a good plan. One approach is to evaluate the performance of a plan. A plan that maximizes the goals achieved and minimizes the resources consumed is a superior plan. The problem is that plans sometimes succeed or fail for reasons that have little to do with the quality of the plan itself. For example, low-probability events in the environment may undermine a plan that would otherwise outperform alternative plans.

Another approach is to evaluate a plan against various criteria. The problem with this approach is that there are many possible criteria, and individuals may differ in the significance they attach to particular ones. In addition, some criteria may conflict with one another. For example, the planner can try to formulate a plan that includes many goals or a plan that includes the most important goals. It is not always possible to satisfy both criteria with a single plan. Individuals may differ in their judgments about which criteria to compromise in such situations

Our approach to the assessment of planning performance was to create a simulated planning environment with which subjects could interact. Subjects formulate plans and submit them to a computer program which then simulates plan execution. The program provides feedback regarding the plan's outcomes and the vari-

ous attributes of the plan that contributed to its outcomes. For example, the subject might learn that execution time ran out before all of the goals were achieved and that this happened because his time estimates were unrealistic. Based on these attributes, the program also computed and reported an overall plan score. We allowed subjects to interact with the simulated environment on several trials. In the course of these interactions, subjects learned about the environmental contingencies that might impact on their plans and about the criteria that would be used to evaluate their plans. We evaluated subjects in terms of their asymptotic plan scores. Thus, our evaluation of their performance was not confused by surprising environmental contingencies or by individual differences in planning criteria. It was a relatively pure measure of the subject's ability to plan in accordance with a known set of contingencies and criteria.

VI. PRELIMINARY PRINCIPLES FOR IMPROVING PLANNING PERFORMANCE

The body of research summarized in this Report suggests a number of principles for improving planning performance, as outlined below

CRITERIA FOR SELECTING PLANNERS

1. *Large-capacity working memory.* The opportunistic model describes people's tendency to "jump around" the space of possible considerations while forming plans. This suggests that it may be important for planners to have large-capacity working memories in order to keep track of several aspects of a developing plan simultaneously.

2. *Attentional flexibility.* Our studies of individual differences in planning performance showed that good planners shift attention among different aspects of a planning problem more frequently than poor planners. Therefore, attentional flexibility may be another important characteristic of potential planners.

3. *Strategic flexibility.* Our studies of top-down versus bottom-up planning strategies showed the impact of particular planning strategies on the efficacy of the plans subjects produce and on the efficiency with which they produce them. In addition, some subjects appeared more willing than others to adopt alternative strategies. Therefore, strategic flexibility may be another important selection criterion.

WHAT TO TEACH PLANNERS

4. *Concepts of abstract plans, world knowledge decisions, metacognitive decisions, and executive decisions.* Our studies of individual differences showed that good planners made decisions in all categories of the planning blackboard, whereas poor planners made only certain kinds of decisions. In particular, high-level abstract decisions, world knowledge decisions, metacognitive decisions, and executive decisions distinguished good planners from poor planners. Therefore, planners should be taught the roles of these types of decisions in the planning process.

5. *Domain-specific planning heuristics.* Our studies of individual differences also showed that good planners had more different planning specialists than poor planners. Therefore, planners should be taught a variety of domain-specific planning heuristics.

6. *Costs and benefits of opportunism.* There is considerable evidence that most people employ some amount of opportunism in the planning process. Opportunism provides planners freedom to examine various aspects of a problem, investigate alternative plan configurations, etc. This enables them to discover solutions that more rigid approaches would obscure. On the other hand, opportunism requires additional time and may lead planners down unproductive, as well as productive,

solution paths. Planners should be taught these advantages and disadvantages and how to exercise controlled opportunism.

7. *General planning strategies.* As mentioned above, different planning strategies are appropriate under different circumstances. Planners should be taught general planning strategies and the circumstances under which each is appropriate.

8. *Judgment and time estimation.* Most people show a strong tendency to underestimate the time required for planned actions. As a consequence, their plans are unrealistic and overrun the time available for execution. Planners should be taught cognitive methods for making such judgments more reliably and more accurately.

HOW TO TRAIN PLANNERS

9. *Provide explicit instruction.* Explicit instruction appears to be a highly effective technique for training particular planning strategies and methods.

10. *Induce illustrative experiences.* Many planners seem to be able to generalize what they learn from one planning problem to subsequent, similar planning problems. Therefore, general strategies and methods can be taught by instructing planners how to use them on specific problems and providing opportunities for them to generalize them to similar problems.

11. *Illustrate effective planning with a simulation.* Because our planning simulation effectively mimics the cognitive processes people use while planning, it may provide a useful model during training. The simulation could be programmed to illustrate alternative planning strategies.

EFFECTIVE AIDS FOR PLANNERS

12. *Aids for reliable estimation of resource requirements.* Even with training, people may not be able to generate reliable and accurate estimates of resource requirements. However, it would be fairly straightforward to develop computer aids for generating these estimates.

13. *Plan-evaluation aids.* People appear to be better at generating plans than they are at evaluating them. It would be useful to have aids that evaluated a plan's feasibility and efficiency against some model of the plan execution environment.

14. *A planning collaborator.* Planning is a complex problem. Even the sophisticated cognitive skills people possess do not always produce optimal or even satisfactory plans. It would be useful to have a planning collaborator that suggested useful planning strategies and heuristics and contributed specific decisions to the plan in progress.

While these principles must be regarded as preliminary, they follow from a substantial and integrated body of research. We believe that they provide a firm foundation for future research on planning and for the development of improved planning technologies.

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